RESEARCH TRAINING IN UNSTEADY SLUDGE INCINERATION

An ASSERT Project

Final Report

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14. ABSTRACT

This ASSERT program supported a parent investigation of the advantages of pulse combustion in solid waste and sludge incineration. Four auxiliary studies were, at least in part, funded under this program. A phenomenological model was developed which was used to understand the interaction between heat release and in a pulse combustor acoustics. It was shown that the convection time of reactive mixture pockets in the pulse combustor determine the level of acoustic driving. Furthermore, it was determined that while pulsations significantly enhance surface evaporation, they do not noticeably accelerate the migration of moisture or vapor from the inside of particulate matter to its surface. It was further determined that variable cross-section pulse incinerators result in larger dB levels than in straight ducts. Nevertheless, the development of dissipative traveling shocks is suppressed. Finally, an injector was developed that is capable of modulating the supply of liquid fuel or fine slurries at frequencies up to 800 Hz. While much of the above findings are also applicable to a variety of other pulse combustion applications, they provide important information for the construction of pulse incinerators, which have, in the parent project, been shown to provide significant advantages, over traditional furnaces.

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Introduction

The subject ASSERT program provided partial support for four graduate students performing research related to sludge spray formation and combustion in acoustically driven turbulent flows.

The parent grant dealt with the determination of the feasibility, performance and benefits of a novel actively controlled, pulsed, shipboard sludge incinerator. In this incinerator thermal and acoustic energy are supplied by a tunable pulse combustor. The unsteady exhaust flow of the pulse combustor atomizes the slurry while the acoustic field in the incinerator increases heat and mass transfer between the air and spray, thus, accelerating the evaporation and combustion of the slurry droplets. In addition the effect of pulsation on the combustion of solid waste was investigated.

In the parent study two approaches were taken towards the development of a suitable pulse combustor. The first approach was the development of a tunable pulse combustor that can force resonant oscillations in the incinerator chamber. The second approach was to develop a high amplitude, low frequency pulse combustor that can generate non-resonant oscillations in the incinerator chamber. While tunable systems are more attractive for the generation of high amplitude oscillations in the incinerator, they currently have shortcomings, such as their inability to operate on liquid fuels. A single frequency, oil burning pulse combustor was demonstrated, and the use of this type of combustor appears to be the more practical approach at this time.

Tests were performed to show that the hot, oscillating exhaust of a pulse combustor can be used to atomize a stream of liquid, and that this may be useful for replacing the two-phase atomizer currently used to spray sludge into the incinerator. Pulsed incineration tests were performed using a gas fired burner that could be operated at 80Hz, 240Hz, and in steady state mode. Operation in the 80Hz mode modeled the oil burning pulse combustor. The use of this combustor allowed comparisons to be drawn between different modes of excitation,which could not be achieved using the oil burner. The heat losses from the incinerator chamberwere greatly increased in the presence of pulsations, and the gas fired pulse combustor was shown to emit roughly 50% less nitrogen oxides when operated in a pulsating mode. Despite increased heat losses and the subsequent lower chamber temperatures, the evaporative efficiency of the incinerator was typically 50% greater when oscillations were excited in the chamber. Tests were also performed in which methanol and sugar solutions were used as liquid waste surrogates, but low chamber temperatures resulted in unreliable results.

Another part of the study showed that pulsations enhance the combustion of solid waste in both laminar and turbulent flows. While the effect is larger in laminar flows, the consumption rate of samples was doubled by the acoustics even in turbulent flows. The study further showed that acoustic velocity rather than pressure fluctuations cause the observed enhancement. These velocity fluctuations increase the transport of oxygen to the burning surface while enhancing the removal of combustion products, including ashes. These enhanced transfer rates are the cause for the increased combustion rate described above.

Four additional physical processes were investigated that are related to the parent project. These are in order in which they are described below:

I. A theoretical model was developed that describes the mechanism by which pulsations are produced in a combustor that can be used to drive a pulse incinerator.

II. The mechanism by which pulsation remove moisture from wet particulates was investigated.

III. The effect of incinerator geometry on the propagation of pressure pulses in the reactor was investigated.

IV. Finally, a pintle type liquid injector was developed which can pulse the injection of Fluids, such as liquid fuels or sludges, at frequencies up to 800Hz.

The results of the above investigations have significant implications beyond the incineration of solids and sludges. However, their development has, at least in part, been funded by the ASSERT program.

Modeling of Combustor Driving

This study investigated the formation of combustion driven oscillations in combustors that would be used to drive the pulsations in unsteady waste incinerators. It consists of complimentary theoretical, experimental, and numerical investigations of unsteady combustors. It was shown that such systems can be destabilized by a feedback mechanism between heat release, pressure, and equivalence ratio oscillations. An analytical stability model was developed to clarify the important features of this mechanism. This quasi-one dimensional linear acoustic model solves the wave equation separately in the inlet, combustor, and exhaust sections. The motions in each section are coupled by specifying momentum and energy conservation conditions at the interfaces between sections and boundary conditions at the up and downstream ends of the facility. The model results indicate that the phase between the combustor pressure and velocity at the fuel injector, the time required for the reactive mixture to convect from the fuel injection point to the flame, and the acoustic period play key roles in the stability characteristics of premixed combustors. A number of experiments were performed using a premixed combustor and the results were found to closely agree with the key predictions of the model.

In order to clarify the nonlinear processes controlling the finite amplitude combustor oscillations during an instability, experiments were performed to characterize the limit cycle

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near field of the flame must be taken into consideration in analyses of the interactions between acoustic waves and flames.

Particulate Drying

In a separate study the effect of pulsations on the evaporation of moisture from particulates was investigated. This work has direct relevance to the problems associated with the incineration of sprayed slurries which must be preceeded by the removal of water. In this work poly (ethylene) terephthalate (PET) was used as the sample because its drying process is also of interest to the chemical industry.

The significant advantage of acoustically enhanced drying processes is that the drying rate can be increased without increasing the temperature of the drying medium. Therefore, acoustic oscillations are often able to decrease drying times in cases where the temperature of the drying medium cannot be increased due to material, process or thermodynamic limitations. Previous studies have shown that acoustic drying rates of up to 4.75 times the non-acoustic drying rate can be achieved in a rotary kiln dryer when drying solids which are completely covered with moisture.

In the experiments, reported here, samples of PET were weighed and placed in a convection air dryer which was designed and constructed for use in the Aerospace Engineering Combustion Laboratory. The samples were dried with and without acoustic oscillations in heated nitrogen at flowrates ranging from 110 scfh to 300 scfh. The sound pressure level of the acoustic oscillations varied from 140 dB to 150 dB. Resonant frequencies of the facility were determined from the resonant tube length measured between the top of the dryer and the PET surface, along with the temperature distribution in the tube. The relative humidity of the outgoing air was measured by pulling a sample of the exhaust gas across a polymer film hygrometer. The drying rate of the sample was computed from the relative humidity and temperature data. The sample was considered dry when the relative humidity values were 0.0% RH. The drying rate curves were compared for the acoustic and non-acoustic cases. After an initial increase in the evaporation of surface moisture, no increase in the drying or heating rate of the sample was observed. This suggest that the velocity fluctuations, which are believed to be responsible for increased heat transfer to and moisture transfer from the sample, are only effective on the particulate surface. Increased migration of moisture from the inside of the particulates to its surface appears not to be affected by pulsatons in spite of steeper moisture gredients present in the particle in the prescence of acoustics.

To confirm this hypothesis a household sponge was saturated with water and dried in nitrogen at 10 scfh and 70 F in the presence of acoustic oscillations. Using the same procedure as was used in the PET drying evaluations, we were able to show an acoustic drying rate of 3 times that without acoustics. Further, the total time to dry the sponge was reduced by as much as 36%. The fact that pulsation enhance drying of a sponge with a large surface to volume ratio lends further credence to the conclusion that acoustic enhancement of drying is limit to surface moisture.

Effect of Variable Geometry

In this study the generation and propagation of strong acoustic pulsations in variable area ducts was investigated. Finite amplitude acoustic waves can be significantly influenced by nonlinear gasdynamic properties arising from the convective terms in the equations of motion for a compressible fluid. The effect of these nonlinearities results in the generation of higher harmonic frequencies, which can be perceived as a distortion of the original waveform. According to the equations of motion, these harmonic frequencies will be integer multiples of the fundamental frequency of the wave. If the generation of harmonics is significant enough, discontinuities (shocks) result, providing increased dissipation of useful acoustic energy.

The original work done on finite amplitude waves in ducts dealt primarily with cylindrical ducts forced at or near the linear fundamental frequency. The results of such work both experimentally and theoretically revealed a 'sawtooth' waveform for relatively large forcing amplitudes. The pressure waveform is characterized typically by a shock front and a relaxation zone. The shape of this waveform is determined largely by nonlinear gasdynamic properties. Consequently, the waveforms are predicted satisfactorily by approximately solving a nonlinear wave equation. A fundamental difference between cylindrical ducts and variable cross-section area ducts lies in the relationship between the fundamental linear resonance frequencies and the higher harmonics. In a cylindrical duct it can be shown that the harmonics are integer multiples of the fundamental, whereas in a variable area duct higher harmonics are more often than not non-integer multiples of the fundamental. One important effect due to this difference lies in the ability of the system to transfer energy from the fundamental mode to the higher harmonic modes. Commonly referred in the literature as 'detuned', these variable area ducts suppress energy transfer to higher harmonics.

A quasi-one dimensional model of nonlinear finite amplitude acoustic oscillations in closed ducts was developed. The model is based on a perturbation expansion about mean conditions of the dissipative one dimensional governing equations of motion for a fluid within a closed duct of variable area. Nonlinear terms arising from the expansion of the equations are retained up to second order. The Galerkin Method, an application of the Method of Weighted Residuals, was employed to obtain approximate solutions to the resulting nonlinear dissipative wave equation. It is unique in that the weighting function used to minimize the residual is the 'trial' function used in the expansion of the dependent variable. An approximate solution of the following type is assumed:

$$p(x,y,z,t)=\sum_{n=1}^{\infty}\Psi_n(t)\Theta_n(x,y,z). \tag{1}$$

(In (1), p is the dependent variable which can be a function of several independent variables. Furthermore, Θ_n is a set of 'trial' functions which must be both mutually orthogonal and form a complete set for the Galerkin Method to be properly implemented. In the Galerkin Method, the choice of 'trial' functions is often determined by a simpler problem with similar though not identical properties. For this study, the trial functions were chosen based on the linearized unforced version of the problem. The advantage of the Galerkin method is that a judicious choice of the trial functions allows for the system to be adequately described using a smaller number of expanded terms than that of an arbitrary expansion. The approximate solution is then substituted into the differential equations of interest thus forming the following residuals:

$$R_n(p)=N\left(\sum_{m=1}^{j}\Psi_m(t)\Theta_m(x,y,z)\right)-f(x,y,z,t) \tag{2}$$

where N represents the nonlinear operator with the expanded dependent variable and f represents the actual operator. The minimization of the residual by integrating over the volume (dV=dxdydz) results in a set of coupled nonlinear ordinary differential equations in time:

$$\int_V \Theta_k R_n dV=0 \quad \text{for } k=0,1,2,3,\ldots n \tag{3}$$

which can then be numerically integrated. Use of the Galerkin Method as a means of obtaining an approximate solution to the partial differential equation provides a functional representation of the system in terms of the linear natural modes. The resulting set of functions describes the physical system as a set of nonlinear coupled oscillator equations.

The pressure fields from several ducts with different area profiles were examined and compared. For all cases , the system was sinusoidally forced at the fundamental resonance frequency. It was shown that the pressure amplitude in variable area ducts is much larger than that in cylindrical ducts. In addition, the resulting waveforms for variable area cases also appear to be free of shocks. This results in a decrease in the amount of acoustic energy dissipated. Preliminary results, which agree with previous experimental observations suggest increased maximum pressure amplitudes, fifteen times those observed in cylindrical ducts. However, the characteristic "saw tooth" shape of the pressure fluctuations was no longer observed and, therefore, highly dissipative shock waves may be assumed to be no longer present. Comparisons of model results to previously published experimental work is currently being completed using internal funding. The results will also be used to further examine the mechanism of the suppression of higher harmonics due to the influence of the shape of the duct on linear natural frequencies.

Novel Injector

Finally, a pulsed spray combustion control system was developed which produces heat release oscillations by pulsing the fuel flow rate through a pintle type fuel injector. Its effectiveness was evaluated by determining the percentage of fuel injected that produced heat release oscillations. CH* emission was used to characterize the heat release experimentally. The entire flame was characterized in a single test run. The data was then divided into several slices, and analyzed individually. The data was processed to determine the percentage of fuel burned that produced oscillations. The axial phase distribution of the CH* oscillation was also determined. This information was then used with the Rayleigh criterion to determine which part of the flame drives or dampens the oscillation. Square wave control signals were investigated in the 170-800 Hz range at several duty cycles. The percent duty cycle reflected the amount of time that the pintle spent in the closed position. The influence of the control signal properties on the effectiveness was then evaluated. Also, the flame was filmed using high-speed photography, and the fuel spray was characterized using a Phase Doppler Particle Analyzer to better understand its behavior. The most effective results were obtained when the fuel was injected as brief high-pressure bursts. For the injector used in this study, this corresponded to control signals with low frequencies and high duty cycles.

Conclusions

This ASSERT program supported a parent investigation of the advantages of pulse combustion in solid waste and sludge incineration. Four auxiliary studies were, at least in part, funded under this program. A phenomenological model was developed which was used to understand the interaction between heat release and in a pulse combustor acoustics. It was shown that the convection time of reactive mixture pockets in the pulse combustor determine the level of acoustic driving. Furthermore, it was determined that while pulsations significantly enhance surface evaporation, they do not noticeably accelerate the migration of moisture or vapor from the inside of particulate matter to its surface. It was further determined that variable cross-section pulse incinerators result in larger dB levels than in straight ducts. Nevertheless, the development of dissipative traveling shocks is suppressed. Finally, an injector was developed that is capable of modulating the supply of liquid fuel or fine slurries at frequencies up to 800 Hz. While much of the above findings are also applicable to a variety of other pulse combustion applications, they provide important information for the construction of pulse incinerators, which have, in the parent project, been shown to provide significant advantages, over traditional furnaces.